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In search of homelands: using strontium isotopes to identify biological markers of mobility in late prehistoric Portugal

Anna J. Waterman[a,*], David W. Peate[b], Ana Maria Silva[c], Jonathan T. Thomas[a]

[a] The University of Iowa, Department of Anthropology, 114 Macbride Hall, Iowa City, IA 52242, USA
[b] University of Iowa, Department of Earth & Environmental Sciences, 121 Trowbridge Hall, Iowa City, IA 52242, USA
[c] University of Coimbra, Department of Life Sciences, University of Coimbra, Coimbra 3001-401, Portugal

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ABSTRACT

This study uses strontium isotopes ($^{87}Sr/^{86}Sr$) in dental enamel from burial populations related to the fortified Chalcolithic settlement site of Zambujal (c. 2800–1800 BC) to distinguish the presence of non-local individuals. Zambujal is located in the Estremadura region of Portugal near the Atlantic coast and has long been considered a central location of population aggregation, craft production, and trade during a time of increasing political centralization and social stratification until its eventually abandonment during the Bronze Age. While it is assumed that population migration and long distance trade played an important role in the region's development, little is known about the migration patterns of individuals or groups. The results of this study find that nine percent (5 out of 55) of the total surveyed individuals can be classified as non-local (based on $^{87}Sr/^{86}Sr$ values distinct from the local bioavailable range of 0.7090–0.7115 as defined by 2sd of the sampled human mean), the majority of which come from one burial site, Cova da Moura. Comparisons with other regional data suggest the possibility that some of these non-locals come from the Alentejo region of the Portuguese interior, corresponding with known exchange patterns.

1. Introduction

The archaeological record of the Late Neolithic through Early Bronze Age in the Estremadura region of Portugal (Fig. 1) provides clear evidence of the rise of a socially-complex, chiefdom-scale non-state society (Cardoso, 2007; Gonçalves, 1999; Lillios, 1995). While several settlement sites in this area have been discovered (including Fórnea, Pico Aguda, and Boiaca), the most prominent and well-excavated is the walled fortification of Zambujal (c. 2800–1800 BC), which has long been considered a center of trade, population aggregation, craft production, and metallurgy in this region until its eventual abandonment during the Bronze Age (Kunst, 1995; Sangmeister and Schubart, 1981; Uerpmann and Uerpmann, 2003). While it is assumed that population mobility and long distance trade played an important role in the development of social complexity in the region, very little is known about the migration patterns of individuals or groups. Therefore, this study uses strontium isotope ratios ($^{87}Sr/^{86}Sr$) in dental enamel to distinguish non-local individuals from seven Late Neolithic-Early Bronze Age (3500–1800 BC) burial populations related to Late Neolithic and Copper Age settlement sites, in particular Zambujal, near the municipality of Torres Vedras in the Estremadura region (Fig. 1).

$^{87}Sr/^{86}Sr$ isotope ratio ranges are available for some geological formations and groundwater samples in the Iberian Peninsula (e.g. Freitas et al., 2003; Moita et al., 2009; Schneider et al., 2009; Villaseca et al., 2009; Voerkelius et al., 2010), and predictions can be made based on the lithologies and ages of different geological units. However, with the exceptions of preliminary studies by Ortega et al. (2012), Prevedorou et al. (2010) and Boaventura et al. (2010), specific measurements of bioavailable $^{87}Sr/^{86}Sr$ isotope ratios are unavailable for most of Portugal and Spain. Thus, this study marks a crucial first step in connecting past peoples and animals with particular geographic regions using $^{87}Sr/^{86}Sr$ isotope ratios in the Iberian Peninsula.

2. Strontium isotope ratios and landscapes

In archaeological research, the measurement of radiogenic strontium isotope ratios ($^{87}Sr/^{86}Sr$) in biological tissues can be used

* Corresponding author. Present address: Mount Mercy University, Department of Natural and Applied Sciences, 150 Basile Hall, Cedar Rapids, IA 52402, USA. Tel.: +1 319 400 5779.

E-mail addresses: anna-waterman@uiowa.edu, awaterman@mtmercy.edu (A. J. Waterman), david-peate@uiowa.edu (D.W. Peate), amgsilva@antrop.uc.pt (A. M. Silva), jonathan-thomas@uiowa.edu (J.T. Thomas).

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Fig. 1. Map of the Estremadura and Alentejo regions of Portugal.

to identify human and animal migration patterns (see Beard and Johnson, 2000; Bentley, 2006; Price et al., 2002, 2012). This is possible because the strontium isotope signature of each particular geographic area permeates the landscape and local groundwater and is absorbed into the local plants and residing animals. Strontium is incorporated into teeth and bone through water and food intake. Due to its close chemical affinity, it substitutes for calcium in the mineral component (hydroxyapatite) of hard tissues (Bentley, 2006; Ericson, 1985; Nelson et al., 1986; Schroeder et al., 1972:496). Radiogenic strontium isotopes ($^{87}Sr/^{86}Sr$) do not fractionate when absorbed into human and animal tissues, and thus an organism's strontium isotope signature directly reflects the bioavailable strontium in its environmental range. Therefore, animals and humans occupying the same territorial ranges and ingesting only local plants, animals, and water, should bear similar strontium isotope signatures. Conversely, between regions that are geologically distinctive, humans and animals should exhibit differences in strontium isotope ratios according to the local lithology. When significant geologic heterogeneity exists in larger regional landscapes it is possible for humans and/or animals to migrate into areas in which the local bioavailable $^{87}Sr/^{86}Sr$ ratio deviates enough from that of the home range for this difference to be clearly identifiable in analyses of hard tissues. This approach requires geologic diversity over transversable distances, and thus our study area in central Portugal should be amenable to strontium isotope fingerprinting of human migration given the wide range of rock types of different ages present in the region (Fig. 2). However it is important to clarify that this methodology is unable to distinguish between individuals who originate from different locations that share similar bioavailable $^{87}Sr/^{86}Sr$ values, and therefore the number of migrants recognized will provide only a minimum estimate of mobility.

2.1. Geology of the Estremadura

The Estremadura region of southwestern Portugal borders the Atlantic coast and encompasses both the Lisbon and Setúbal peninsulas (Fig. 1). Geologically the region is quite diverse, occupying part of the Lusitanian Basin, a northern Atlantic basin formed during a rifting phase of the late Triassic. This basin, which is mainly composed of Cretaceous and Jurassic sediments with pockets of Triassic sediments in the north, connects to the Alentejo and the Algarve Basins in the southeast, and is delineated in the north and east by the Late Paleozoic Hercynian basement rocks of the Iberian Meseta (Cunha and dos Reis, 1995; Wilson, 1988) (Fig. 2). The landforms of the Lusitanian Basin are geologically younger than other parts of the Iberian Peninsula and are mainly composed of heterogenous lithologies including limestones, sandstones, clays, marls, basalts and volcanic rocks (Azerêdo et al., 2002; Wilson, 1988). In general the Lusitanian Basin lacks many of the igneous granites and metamorphic schists found in the Portuguese interior, although some intrusive massifs of granites are found west of Lisbon near the municipality of Sintra (Sparks and Wadge, 1975). The Lusitanian Basin is further divided by faults into the Northern Lusitanian Basin, the Central Lusitanian Basin, and the Southern Lusitanian Basin (Schneider et al., 2009). In the northeast of the Central Basin the landscape is dominated by Jurassic marine limestone massifs, while in the inland west and south, Jurassic limestones are interspersed with large areas of Cretaceous sandstones and conglomerates (Schneider et al., 2009). Basalts are prevalent in the volcanic complexes around Lisbon and in the southeast of the region the lowlands of the lower Tagus basin are mainly composed of Triassic sandstones. Rivers, including the Almonda and the Nabão originate in the northern highlands and cut through the southeastern Tagus Tertiary Basin where Miocene

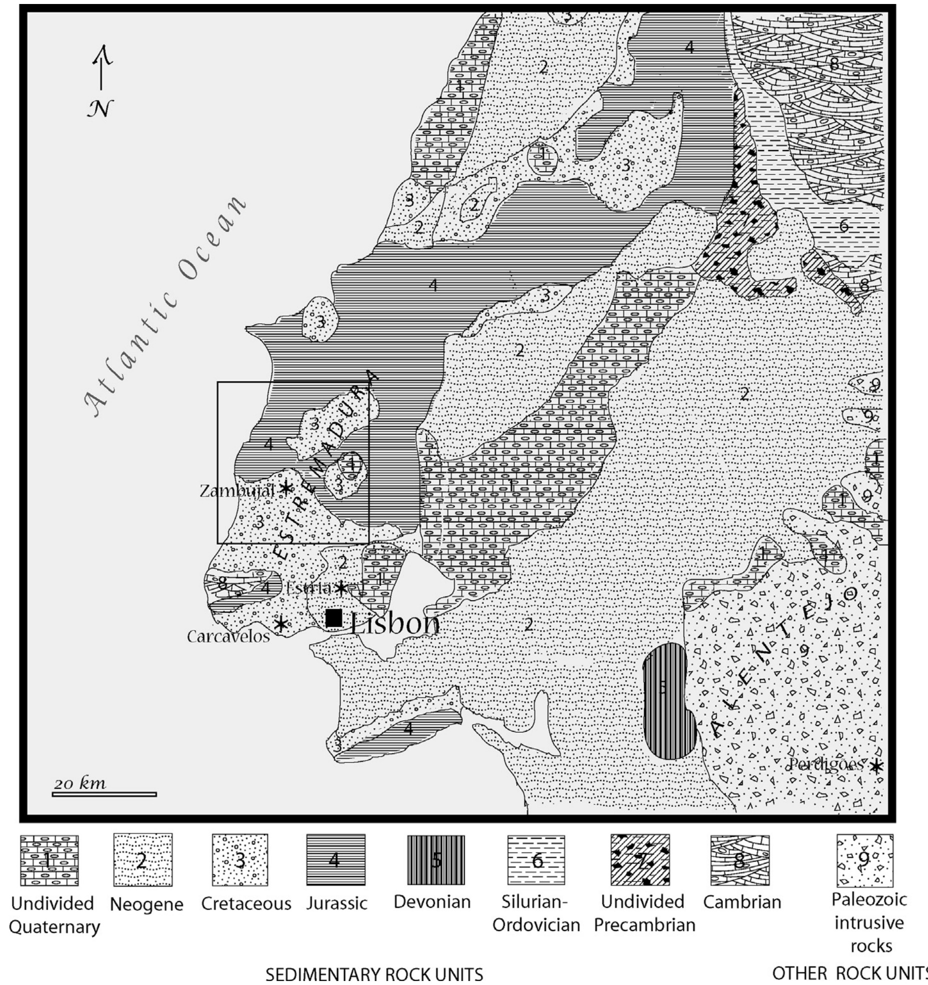

Fig. 2. Simplified geological map of the areas of the Portuguese Estremadura and Alentejo discussed in the text. Box indicates region of burials surrounding Zambujal.

sediments include sandstones, clays and conglomerates (Antunes et al., 1999; Marks et al., 1994). Numerous karstic caves systems permeate the landscape. The plentiful caves and alkaline soils of the region provided an excellent environment for the preservation of archaeological and biological materials. The carbonate-dominated Mesozoic sediments of the Lusitanian Basin are expected to have $^{87}Sr/^{86}Sr$ close to marine values (0.707–0.710: e.g. Schneider et al., 2009), or slightly higher depending on the contribution of clastic deposits (local water analyses have $^{87}Sr/^{86}Sr$ of 0.709–0.711: Voerkelius et al., 2010). Additionally, as this is a coastal region, seawater rainfall and sea spray incorporation into the terrestrial food chain may also lead to $^{87}Sr/^{86}Sr$ ranges that are close to seawater values (Bentley, 2006). In contrast, the older Paleozoic Hercynian basement metamorphic and granitic rocks of the interior should generally have more radiogenic values ($^{87}Sr/^{86}Sr > 0.713$: e.g. Bea et al., 2003).

3. Materials and methods

3.1. Selected archaeological sites

While the goal of this study was to analyze human skeletal remains related to the settlement complexes associated with the fortified site of Zambujal in order to investigate mobility patterns in this region, human settlements and burial places were geographically separate in the Estremadura region of Portugal during the Late Neolithic and Copper Age. Consequently, with the exception of a small amount of dental remains from three individuals recovered from the ruins of Zambujal itself, all other sampled humans are drawn from contemporaneous burials in the surrounding region that are believed to house the dead of communities related to Zambujal.

Human remains were selected from six collective burial sites located within 25 km (15 miles) of Zambujal near the city of Torres Vedras (Fig. 3). The included sites are: (1) The natural cave burial site of Cova da Moura (Belo et al., 1961; Gallay and Spindler, 1970; Silva, 2003; Spindler, 1981); (2) the natural cave burial site of Feteira II (Waterman and Horwath, 2009; Waterman, 2012); (3) the natural cave burial site of Lapa da Rainha II (Kunst and Trindade, 1990; Waterman, 2012); (4) the artificial cave (rock shelter) burial site of Bolores (Kunst and Trindade, 1990; Lillios et al., 2010); (5) the artificial cave (rock cut tomb) site of Cabeço da Arruda I (Silva, 2002, 2003; Trindade and da Veiga Ferreira, 1956); (6) the large burial tholos of Paimogo I (Tholos de Pai Mogo I) (Gallay et al., 1973; Silva, 2002, 2003; Spindler and Gallay, 1972). These sites are diverse in terms of their funerary context, perhaps representing differences in social status by burial type (Waterman, 2012), and span the Late Neolithic through Early Bronze Age (3500–1800 BC), coinciding with the time period in which Zambujal grew, flourished and was eventually abandoned.

3.2. Sampled materials and methods

When evaluating the strontium isotope ratios in hard tissues it is important to make a distinction between bone and dental enamel

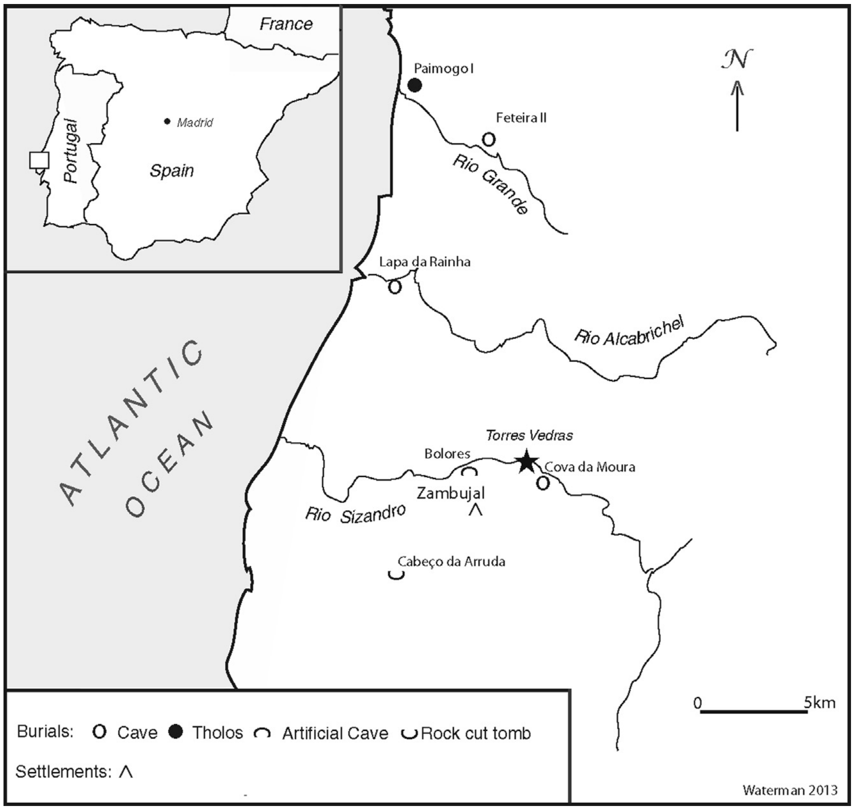

Fig. 3. Map of Burial Sites in the Torres Vedras region used in this study.

when it comes to strontium uptake. Bone remodels throughout life in response to stress, strain, and calcium homeostasis (Manolagas, 2000), therefore, the strontium isotope signature in bone may change over time if a person moves into a new region or consumes non-local foods. This means that a previous native strontium isotope signature in bone may be altered or eradicated in time making it difficult to distinguish between native and migrant individuals from their bones alone. In contrast, dental enamel does not remodel during life (Simmer and Hu, 2001) and therefore preserves the strontium isotope signal from the time of original dietary uptake during enamel formation. For the permanent 2nd and 3rd molars used in this study, this formation time is during the first 4–16 years of life (AlQahtani et al., 2010). Enamel is also more robust with respect to diagenesis and alteration than bone (e.g. Price et al., 2002), and thus, it can be expected to retain the original bioavailable strontium isotopic signature more consistently.

When seeking to discern the presence of individuals of non-local origin in a burial population, it is first important to define the local bioavailable $^{87}Sr/^{86}Sr$ isotope composition. Two established methods to estimate the local $^{87}Sr/^{86}Sr$ range for archaeological samples are: 1. using the mean of human dental enamel analyzes $\pm$ 2 s.d. (Bentley et al., 2004; Price et al., 2001), or, 2. using local faunal remains. In particular, tooth and bone samples taken from animals with very limited geographic ranges (e.g. *Oryctolagus* [rabbits], *Helix* [snails], or other small fauna) recovered from the same archaeological sites where the human population sample is drawn provide the best faunal estimate of the local $^{87}Sr/^{86}Sr$ range (Bentley et al., 2004; Price et al., 2002). Additionally, Price et al. (2002) propose that samples from larger fauna be included as well, as a clear understanding of the migration ranges of multiple species will help to inform our understanding of human migration patterns. In accordance with these suggested practices, in this study $^{87}Sr/^{86}Sr$ isotope ratios derived from large and small fauna (*Bos* [cattle], *Helix* [snails], *Oryctolagus* [rabbits], *Ovis/Capra* [sheep/goat], and *Sus* [pigs]) were examined and compared with the human data. As dietary intake influences $^{87}Sr/^{86}Sr$ isotope ratios in calcified tissues, it is important to consider dietary practices when examining human strontium ranges. In particular, a high amount of marine foods in the diet can influence $^{87}Sr/^{86}Sr$ isotope ratios by bringing them closer to the marine range. As the sampled Zambujal community lived in an estuary environment close to the coast, the influence of marine food input should be considered. However, based upon stable carbon and nitrogen analyses recently completed on these same burial populations, diets appear to be based largely upon terrestrial proteins and C_3 plants with little marine input (Waterman, 2012).

For this study, dental remains from 55 humans and 22 animals were selected from the aforementioned sites. Enamel surfaces were first cleaned with acetone and the top layer of enamel was removed to prevent diagenetic contamination (Budd et al., 2000; Price et al., 2002; Wright, 2005). A small amount of enamel (4–10 mg) was then removed for analysis using a Dremel tool and a Dremel 5/64 in. diamond wheel point. Third and second molars were preferentially selected. However, in cases when other molars were not available, 1st molars were used instead. All chemical processing of the enamel samples was carried out in the University of Iowa Department of Earth & Environmental Sciences clean laboratory. Samples were dissolved in 1 mL of 3 M HNO_3, using sonication to aid digestion. Strontium was isolated with Eichrom Sr-spec ion-exchange resins using standard procedures (see Waight et al., 2002). $^{87}Sr/^{86}Sr$ ratios were then measured using a Nu Plasma HR multi-collector inductively-coupled-plasma mass-spectrometer (MC-ICP-MS) in the Department of Geology at the University of Illinois at Urbana-Champaign. Samples were introduced to the machine using a Nu Instruments DSN-100 desolvator system equipped with a nebulizer with an aspiration rate near 0.1 mL min^{-1}. The samples were alternately run with standards (SRM 987, SCS coral and E&A) using a sample-standard-bracketing measurement protocol wherein standards were run every 3–5 samples (Rehkämper et al., 2004). The ^{88}Sr beam intensities for all samples and standards ranged from 4 to 12 V (100 ppb solutions). Masses of ^{83}Kr to ^{88}Sr were measured during a single cycle comprised of 2 blocks of 25 scans (5 s integration per scan) with a 40 s baseline determination using ESA-deflected signals. Instrumental mass bias was internally normalized to an ^{86}Sr/^{88}Sr ratio of 0.11940 and then corrected ratios were normalized to the NIST SRM 987 international standard value of 0.710268 (which had a reproducibility of $\pm$0.000038: 2 s.d., $n = 46$) to correct for day-to-day variability. The SCS coral standard gave ^{87}Sr/^{86}Sr of 0.709176 $\pm$ 0.000016 (2 s.d, $n = 16$). No corrections were necessary for Sr introduced as part of sample production as procedural blanks were <100 pg Sr.

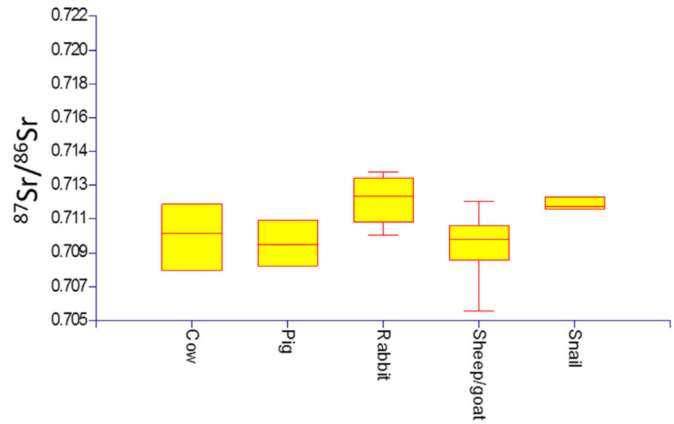

Fig. 4. Box plots of ^{87}Sr/^{86}Sr ratios for fauna.

4. Results

4.1. Faunal results

The results for all the sampled fauna are presented in Table 1 and Figs. 4 and 5. For the three snail shells recovered from soils excavated at Bolores, the ^{87}Sr/^{86}Sr isotope ratios ranged from 0.711221 to 0.711881 with a mean of 0.711517 $\pm$ 0.000335. The low standard deviation in this group likely reflects the extremely limited movement of snails across the landscape, and the fact that the samples were recovered from the same site. The ^{87}Sr/^{86}Sr isotope ratios for the six rabbit samples ranged from 0.709750 to 0.713280 with a mean of 0.711768 $\pm$ 0.001333. All of the rabbits came from the archaeological levels at Bolores, with the exception of one recovered from Zambujal. The range for rabbits was larger than for snails, possibly reflecting a more widespread territorial range. ^{87}Sr/^{86}Sr isotope ratios were also obtained from the pig samples, one from Zambujal and one from Cova da Moura. Like the rabbit sample from Zambujal, the pig samples from Zambujal had an ^{87}Sr/^{86}Sr isotope ratio on the lower end (0.708054) of the overall range of all of the surveyed animals. The ^{87}Sr/^{86}Sr ratios for the seven ovicaprid (sheep/goat) samples ranged from 0.705502 to 0.711643, with a mean value of 0.709212 $\pm$ 0.002. All of the tested ovicaprids were acquired from the site of Zambujal. Despite the fact that all of the ovicaprids were acquired from the same site, they have the largest ^{87}Sr/^{86}Sr ratio range of any of the sampled faunal groups. This most likely is a reflection of diverse foraging behavior of sheep and goats, and the likelihood that the animals may have been brought in from other areas with different bioavailable strontium signatures. One animal in particular, Z1129, has ^{87}Sr/^{86}Sr ratios that are significantly divergent from all of the others (0.705501), the lowest ^{87}Sr/^{86}Sr ratio recorded for any of the animals. The three bovids that were tested exhibited an ^{87}Sr/^{86}Sr isotope ratio range of 0.707795–0.711497, with a mean value of 0.709739 $\pm$ 0.001858. Once again, despite the fact that all of the sampled bovid mandibles were derived from Zambujal, the ^{87}Sr/^{86}Sr isotope ratios were quite varied, although not as variable as the ovicaprid values. These variations likely reflect that bovids were also grazing on diverse landscapes, or that some domesticated animals were being traded into the region from neighboring areas. All of the rabbit samples except one came from the site of Bolores. The non-Bolores rabbit sample was from Zambujal and had a much lower ^{87}Sr/^{86}Sr isotope ratio. The large ranges presented by the animals sampled in this study suggest: 1) more variation in the bioavailable strontium across limited distances than expected, 2) larger animal migration ranges, or 3) long-distance animal trading (Figs. 6 and 7).

Table 1
^{87}Sr/^{86}Sr ratios for fauna.

Site	Genus	Sample	^{87}Sr/^{86}Sr
Bolores	*Helix*	B1.SS.1	0.711881
Bolores	*Helix*	B1.SS.2	0.711448
Bolores	*Helix*	B1.SS.3	0.711221
ave			0.711517
sd			0.000335
Bolores	*Oryctolagus*	B1.X.1.BL1	0.711635
Bolores	*Oryctolagus*	B1.OD.0.BL2	0.712847
Zambujal	*Oryctolagus*	Z87190-40-1	0.709750
Bolores	*Oryctolagus*	B1.11S.5.B868	0.713280
Bolores	*Oryctolagus*	B1.OD.0.BL4	0.710758
Bolores	*Oryctolagus*	B1.11.0.BL54	0.712342
ave			0.711768
sd			0.001333
Zambujal	*Sus*	Z87-82-40-24	0.708054
Cova da Moura	*Sus*	CMF2	0.710593
ave			0.709323
sd			0.001795
Zambujal	*Ovis/Capra*	Z469	0.710296
Zambujal	*Ovis/Capra*	Z492	0.709796
Zambujal	*Ovis/Capra*	Z1136	0.711643
Zambujal	*Ovis/Capra*	Z1143	0.709284
Zambujal	*Ovis/Capra*	Z87-101-40-21	0.709599
Zambujal	*Ovis/Capra*	Z87-101-40-8	0.708368
Zambujal	*Ovis/Capra*	Z1129	0.705502
ave			0.709212
sd			0.001917
Zambujal	*Bos*	Z829	0.707795
Zambujal	*Bos*	Z812	0.711497
Zambujal	*Bos*	Z10000	0.709925
ave			0.709739
sd			0.001858

4.2. Human results, defined local range and identified migrants

When the human data from the individual sites are considered, the standard deviations were low in comparison to the faunal remains (Table 2). This result was unexpected. In other studies (e.g. Price et al., 2002), humans typically have greater Sr isotope variability in comparison to small fauna. Because of the large ranges found in the animals in comparison with the human samples, the human samples were used to determine the local bioavailable ^{87}Sr/^{86}Sr isotope ratio range. The mean of the ^{87}Sr/^{86}Sr isotope ratios for the entire human sample with outliers removed is 0.710115. Thus, the local bioavailable ^{87}Sr/^{86}Sr composition for the surveyed region (roughly 25 km^2) is defined as 0.7090–0.7115 (plus or minus 2σ from the sample mean). Based upon this local range, only two

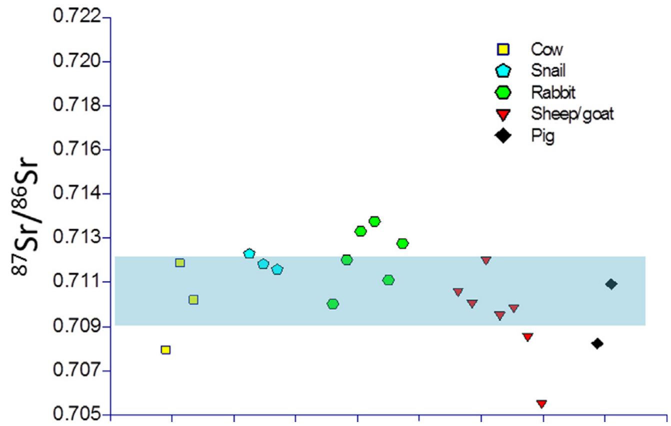

Fig. 5. Scatter chart of $^{87}Sr/^{86}Sr$ ratios for fauna. Local range in blue. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

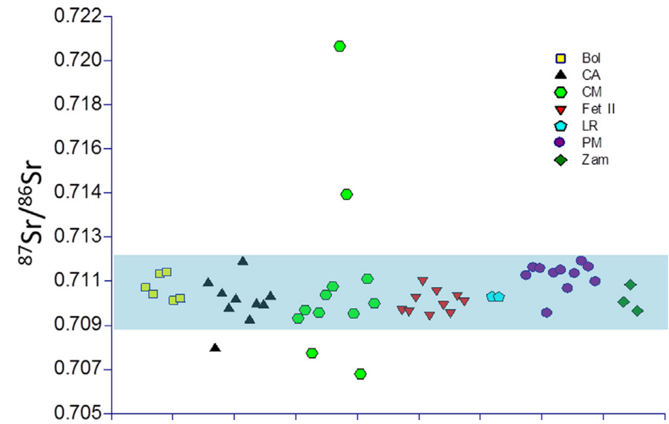

Fig. 7. Scatter chart of $^{87}Sr/^{86}Sr$ ratios for human. Local range in blue. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

burials, Cova da Moura and Cabeço da Arruda I, contained sampled individuals whose $^{87}Sr/^{86}Sr$ ratios were outside the local range (CM 2, CM 95, CM 81, CM 30, and CAI 11).

5. Discussion

For the sampled human population, only 9% (5 out of 55) can be classified as migrants into the region. In most of the sampled burials, no non-local individuals were identified, while the majority of the identified migrants (4 out of 5) come from one site, the large burial cave of Cova da Moura. The only other burial to contain non-local individuals is Cabeço da Arruda I, for which one migrant was identified. In addition to housing 80% of the migrant individuals identified in this study, Cova da Moura is the only burial in which individuals with significantly enriched $^{87}Sr/^{86}Sr$ ratios were found. In particular two individuals from Cova da Moura had $^{87}Sr/^{86}Sr$ ratios between 0.714 and 0.721 (CM 95, 0.720730 and CM 30, 0.714383), reflecting childhoods potentially spent in a region with geologically older features. The high proportion of non-local individuals in the Cova da Moura cave suggests that this burial is somehow socially distinct with 4/12 or 30% of the Cova da Moura sampled individuals having spent at least part of their childhoods elsewhere. Cova da Moura is also an exceptional burial in terms of its relative wealth of well-preserved Late Neolithic and Copper Age artifacts, many of which, such as jet, variscite, and ivory objects, are rare or imported from distant locations (Schuhmacher et al., 2009; Thomas, 2011). However, while all of the burial locations selected in this study were used for hundreds of years, radiocarbon dates from Cova da Moura suggest that burials at this location span a larger temporal window with this cave being used for burials for as long as 1000 years (Cunha et al., 2007). Thus, it is possible that the larger percentage of identified migrants is also related to Cova da Moura's relatively long use-life.

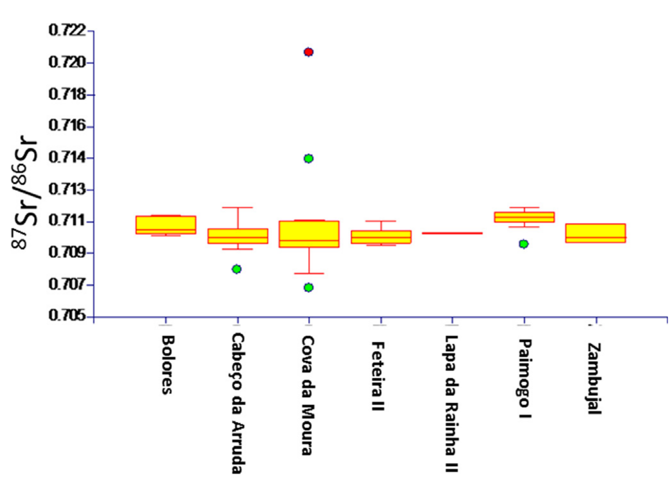

Fig. 6. Boxplots of $^{87}Sr/^{86}Sr$ ratios for humans.

General intersite variability of human $^{87}Sr/^{86}Sr$ ratios is low. The exceptions to this are Cova da Moura, the large cave burial with the greatest number of migrants, and the tholos of Paimogo I, in which human $^{87}Sr/^{86}Sr$ ratios appear to be slightly elevated in comparison to the other burial populations. In contrast, the sampled fauna (with the exclusion of the snails) display more variability, and all animal groups have higher standard deviations than are found in the human burials (Cova da Moura excluded). When considering the variation in the sampled animals, one of the three bovids, one of the two pigs, and two of the seven ovicaprids can be classified as non-local according to the defined local range. All of these possible migrant animals exhibit $^{87}Sr/^{86}Sr$ isotope ratios outside the lower end of the local range as defined by the human population. The majority of the fauna examined in this study and all of the fauna with non-local $^{87}Sr/^{86}Sr$ ratios were recovered from Zambujal. Based upon a cursory investigation of faunal skeletal element distributions from Zambujal while selecting faunal elements to sample, a relative lack of head and lower extremities in comparison with other portions of the skeleton was noted. This may suggest that animals were being butchered elsewhere and that Zambujal may have been the location of final consumption rather than the place where animals were raised and fed. Therefore, variations in the $^{87}Sr/^{86}Sr$ ratios from the animals recovered from Zambujal may be attributable to animals being brought to Zambujal from other areas, possibly for feasting activities or as tribute.

While rabbits are generally considered to be a good animal to use to approximate the bioavailable range because they have limited territorial movement, in this study all of the rabbits but two exhibited $^{87}Sr/^{86}Sr$ ratios above the defined human bioavailable range, included three rabbits which can be classified as non-local according to the defined local human range. As part of the Lusitanian Basin, the Estremadura in general is composed of Cretaceous and Jurassic sediments and lacks many of the igneous granites and metamorphic schists found in the Portuguese interior that would be expected to result in elevated $^{87}Sr/^{86}Sr$ ratios. However, heterogenous lithological features abound at a local scale in the

Table 2
$^{87}Sr/^{86}Sr$ ratios for humans. Migrants marked in bold.

Site	Sample	Age class	$^{87}Sr/^{86}Sr$
Zambujal	Z831/Z970	Adult	0.709783
Zambujal	Z776	Adult	0.710522
Zambujal	Z971	Adult	0.709399
ave			0.709901
sd			0.000571
Lapa da Rainha II	LdR102	Adult	0.710014
Lapa da Rainha II	LdR27	Adult	0.709989
ave			0.710001
sd			0.000017
Bolores	B1.11.4.B114	Adult	0.710401
Bolores	B1.11N.4.B663	Adult	0.710131
Bolores	B1.9/10.0.BL5	Adult	0.710987
Bolores	B1.2.1.B15	Adult	0.711067
Bolores	B1.11S.4.B720	Adolescent	0.709850
Bolores	B1.11S.4.B676	Adolescent	0.709946
ave			0.710397
sd			0.000523
Feteira II	fet1222	Adult	0.709463
Feteira II	fet1219	Adult	0.709411
Feteira II	fet1547	Adult	0.710004
Feteira II	fet342	Adult	0.710712
Feteira II	fet92	Adult	0.709233
Feteira II	fet1245	Adult	0.710281
Feteira II	fet799	Adult	0.709681
Feteira II	fet1229	Adult	0.709338
Feteira II	fet313	Adult	0.710074
Feteira II	fet1006	Adult	0.709838
ave			0.709804
sd			0.000471
Paimogo I	PM 12268	Adult	0.710905
Paimogo I	PM 12263	Adult	0.711243
Paimogo I	PM 12261	Adult	0.711205
Paimogo I	PM 12338	Adult	0.709291
Paimogo I	PM 12951	Adult	0.711009
Paimogo I	PM 12282	Adult	0.711135
Paimogo I	PM 12852	Adult	0.710521
Paimogo I	PM 12600	Adult	0.710988
Paimogo I	PM 12821	Adult	0.710353
Paimogo I	PM 12726	Adolescent	0.711520
Paimogo I	PM 12267	Adolescent	0.711269
Paimogo I	PM 12507	Child	0.710639
ave			0.71084
s.d.			0.000593
Cova da Moura	CM 15	Adult	0.709081
Cova da Moura	CM 12	Adult	0.709443
Cova da Moura	CM 2	Adult	**0.707590**
Cova da Moura	CM 84	Adult	0.709313
Cova da Moura	CM 159	Adult	0.710083
Cova da Moura	CM 9	Adult	0.710438
Cova da Moura	CM 95	Adult	**0.720730**
Cova da Moura	CM 30	Adult	**0.714383**
Cova da Moura	CM 22	Adult	0.709282
Cova da Moura	CM 81	Adult	**0.706697**
Cova da Moura	CM 39	Adolescent	0.710765
Cova da Moura	CM 45	Child	0.709720
ave			0.710627
sd			0.003685
Cabeço da Arruda I	CAI 13	Adult	0.710592
Cabeço da Arruda I	CAI 11	Adult	**0.707792**
Cabeço da Arruda I	CAI 17	Adult	0.710130
Cabeço da Arruda I	CAI 1	Adult	0.709495
Cabeço da Arruda I	CAI 25	Adult	0.709890
Cabeço da Arruda I	CAI 3	Adult	0.711508
Cabeço da Arruda I	CAI 7	Adult	0.709003
Cabeço da Arruda I	CAI 19	Adolescent	0.709686
Cabeço da Arruda I	CAI 2	Child	0.709647
Cabeço da Arruda I	CAI 23	Child	0.710009
ave			0.709775
sd			0.000972

Estremadura, including a variety of limestones, shales, sandstones, clays, marls and conglomerates. The relatively small territorial range of the rabbits increases the probability that different animals may sample different localized lithologies with different $^{87}Sr/^{86}Sr$ isotope values such that the range in $^{87}Sr/^{86}Sr$ for the rabbit population as a whole reflects these local scale lithological variations rather than larger averaged regional patterns that would be sampled by the human population. Apropos to this point, all but one of the sampled rabbits came from Bolores, an artificial cave burial consisting of excavated sandstone with a shale floor. For these archaeologically derived samples, it is possible the higher $^{87}Sr/^{86}Sr$ ratios are influenced by the burial environment as strontium isotopes from the shale floor may have infiltrated the rabbits' hard tissues over time. The lowest $^{87}Sr/^{86}Sr$ ratio for the rabbit group came from Zambujal. This ratio of 0.70975 is more in line with the mean values of the other animal and human groupings. Additionally, within the rabbits' limited territorial range, dietary factors such as plant selection and water source may also influence these animals' $^{87}Sr/^{86}Sr$ isotope ratios. Likewise, the variation in the ovicaprid $^{87}Sr/^{86}Sr$ isotope ratios may similarly reflect differences related to browser dietary patterns and larger variations in their territory ranges. In contrast, the more homogenous human ratios may reflect diets based upon grains grown in the local river valley systems and the use of similar water sources. The inconsistencies between the human and faunal data suggest that additional sampling of small fauna in the region and a closer examination of local geological features may be needed to help clarify the bioavailable $^{87}Sr/^{86}Sr$ ratio ranges in the region.

In a study by Boaventura et al. (2010), humans from the Late Neolithic and Copper Age burial sites of Estria and Carcavelos (approximately 30 km southeast of Zambujal) predominantly exhibited $^{87}Sr/^{86}Sr$ isotope ratios in the 0.706–0.708 range. Thus, we know that the $^{87}Sr/^{86}Sr$ ratios for these relatively close sites are lower than those that were found in the Torres Vedras region in this study. This same study also tested a small sample of human and animals from the settlement site of Perdigões, which lies in the Alentejo region of the Portuguese interior, approximately 200 km southeast of Zambujal. The authors found the local $^{87}Sr/^{86}Sr$ isotope ratios at Perdigões ranged from 0.715 to 0.718, much higher than in the region surrounding Zambujal. These higher isotopic ratios were attributed to the Paleozoic schist and granite rocks which characterize the region (Fig. 2). We know that desirable raw materials such as variscite (Odriozola et al., 2010), slate and amphibolite (Lillios, 1997, 2008), arsenical copper ore (Müller et al., 2007), and other materials from the Alentejo commonly made their way into this part of the Estremadura during this period (Thomas, 2011). The higher $^{87}Sr/^{86}Sr$ isotope ratios exhibited by the migrants identified from Cova da Moura (particularly Adult 7) suggest that people, in addition to goods, were also migrating from the Portuguese interior to the coastal Estremadura.

6. Conclusion

This study uses strontium isotope ratios ($^{87}Sr/^{86}Sr$) in dental enamel to distinguish migrant individuals from seven Late Neolithic-Early Bronze Age (3500–1800 BC) burial populations related to the Late Neolithic and Copper Age settlement complexes of Zambujal located near the municipality of Torres Vedras in the Estremadura region of Portugal. Strontium isotope ratios ($^{87}Sr/^{86}Sr$) were obtained from the dental enamel of 55 humans and 22 animals and the local bioavailable range was calculated as 0.7090–0.7115 using the mean of the human data. Based on this calculation nine percent (5 out of 55) of the total surveyed population can be classified as migrants, the majority of which come from the cave burial of Cova da Moura, marking this site as socially distinct. Two of the non-local individuals from Cova da Moura had $^{87}Sr/^{86}Sr$ ratios that could match the older geologic formations of the Alentejo region of Portugal. This would correspond with known exchange patterns, and suggests that both people and goods were moving into the region from the Alentejo and perhaps vice versa. Surprisingly, the $^{87}Sr/^{86}Sr$ ratios for the fauna were much more heterogenous than for the human data. This was unexpected and suggests that either the fauna (especially larger domesticated animals) had a higher mobility than most of the human populations and/or that the humans largely subsisted on food and water sources from a limited geographic area compared to the fauna. The heterogenous lithological features of the Estremadura may also influence our understanding of the range of faunal variability. Thus, further sampling of small fauna from a larger range of sites would be useful in creating a map of the bioavailable $^{87}Sr/^{86}Sr$ ratios ranges for the region, allowing us to more clearly trace prehistoric human mobility in the Estremadura. While the methodology used in this study can only identify the minimum number of migrants based upon the geological diversity of natal landscapes, comparison of our results with preliminary work from nearby sites (Boaventura et al., 2010) indicate that within a 20–200 km range, there are significant isotopic variations in bioavailable Sr ($^{87}Sr/^{86}Sr$: 0.706–0.708 Estria and Carcavelos; 0.709–0.712 Zambujal; 0.715–0.718 Perdigões: Fig. 2), demonstrating the utility of Sr isotopes for migration studies in this part of the Iberian Peninsula.

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